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14. ABSTRACT
This program conducted experimental research aimed at developing an optically driven quantum dot quantum computer. The work was done in collaboration with D.Gammon at the Naval Research Laboratory and L.J.Sham at UCSD. D.Gammon had responsibility for growing & characterizing the material, L.J.Sham is responsible for theoretical support & concept development. The group at Michigan along with this QuaCGR student are responsible for experimental demonstration of key experimental demonstrations for quantum computing. The original parent program that was funded during the start of this QuaCGR program was aimed at studies of the exciton Bloch vector qubit in neutral quantum dots. The parent program funded during the last part of the QuaCGR grant was aimed at studies of the optical manipulation of the electron spin qubit in charged quantum dots. Work done on this QuaCGR then includes research on both of these approaches. During much of this QuaCGR program, the student focused on demonstrating quantum state tomography. This was most easily approached using neutral quantum dots. The annual reports document the details of this work. In this Final Report, we present the final results of this work, which are now in press in the Physical Review Letters.

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January 18, 2006

Dr. T.R. Govindan
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Dear Dr. Govindan:

Please find enclosed the FINAL Report for contract DAAD19-02-1-0189, proposal number 44057-PH-QC. This report covers the period of June 1, 2002 – August 31, 2005.

If you have any questions, please contact me at 734-647-3875.

Sincerely,

Duncan G. Steel (mc)

Duncan G. Steel
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Enclosures

QuaCGR FINAL REPORT

Optically Controlled Quantum Dot Spins For Scalable Quantum Computing

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ABSTRACT

This program conducted experimental research aimed at developing an optically driven quantum dot quantum computer. The work was done in collaboration with D. Gammon at the Naval Research Laboratory and L.J. Sham at UC-SD. D. Gammon had responsibility for growing and characterizing the material, L.J. Sham is responsible for theoretical support and concept development. The group at Michigan along with this QuaCGR student are responsible for experimental demonstration of key experimental demonstrations for quantum computing. The original parent program that was funded during the start of this QuaCGR program was aimed at studies of the exciton Bloch vector qubit in neutral quantum dots. The parent program funded during the last part of the QuaCGR grant was aimed at studies of the optical manipulation of the electron spin qubit in charged quantum dots. Work done on this QuaCGR then includes research on both of these approaches. During much of this QuaCGR program, the student focused on demonstrating quantum state tomography. This was most easily approached using neutral quantum dots. The annual reports document the details of this work. In this Final Report, we present the final results of this work, which are now in press in the *Physical Review Letters.* In the last part of this program, the student's attention turned to demonstrating ultrafast initialization and control of the electron spin qubit. This work was paralleled by our close collaboration with Lu Sham, whose theory for these experiments preceded our experiments. The experimental work is now completed and presented in this Final Report, and a paper is in preparation.

PUBLICATIONS

JOURNAL PUBLICATIONS

(1) Xiaoqin Li, Yanwen Wu, Duncan Steel, D. Gammon, T.H. Stievater, D.S. Katzer, D. Park, C. Piermarocchi, L.J. Sham, "An all-optical quantum gate in a semiconductor quantum dot," Science. **301**, pp809-811 (2003).

(2) Xiaoqin Li, Yanwen Wu, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, L.J. Sham, "Raman coherent beats from the entangle exciton Zeeman doublet in a single quantum dot," Phys. Rev. B **70**, 195330 (2004).

(3) Yanwen Wu , D. Gammon, L.J. Sham, D.G. Steel, "Coherent Optical Control on the Semiconductor Quantum Dots for Quantum Information Processing" "Physica E. **25**, pp242-248(2004).

(4) M.V. Gurudev Dutt, Yanwen Wu, Xiaoqin Li, D.G. Steel, D. Gammon, L.J. Sham, "Semiconductor quantum dots for quantum information processing : An optical approach", Physics of Semiconductor, José Menéndez and Chris G. Van de Walle, eds, Proceedings of the 27th ICPS, Flagstaff, AZ, American Institute of Physics Vol **772**, p32-37, (2005).

(5) Xiaoqin Li, Yanwen Wu, Xiaodong Xu, D.G. Steel, and D. Gammon, "Transient nonlinear optical spectroscopy studies involving biexciton coherence in single quantum dots," submitted (2005).

(6) Yanwen Wu, Xiaoqin Li,. L. M. Duan, and D. G. Steely D. Gammon, Lu Sham, "Density Matrix Tomography through Coherent Optical Rotation of an Exciton Qubit in a Single Quantum Dot," in press, Phys. Rev. Lett. (2006).

INVITED CONFERENCE PAPERS

(7) Xiaoqin Li, T.H. Stievater, Yanwen Wu, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, Pochung Chen, C. Piermarocchi, L.J. Sham, "Quantum-Bit Rotations in Single Quantum Dots: Rabi Oscillations of Excitons and Biexcitons," QELS 2002.

(8) Xiaoqin Li, T.H. Yanwen Wu, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, Pochung Chen, C. Piermarocchi, L.J. Sham, "Quantum-Bit Rotations in Single Quantum Dots," NOEKS 2003.

(9) Xiaoqin Li, Yanwen Wu, Gurudev Dutt, Duncan Steel, D. Gammon, T.H. Stievater, D.S. Katzer, D. Park, C. Piermarocchi, L.J. Sham, "Quantum Dots as Artificial Atoms: Towards a Quantum Dot Quantum Computer" (IWQDQC) Notre Dame (2003).

(10) Duncan Steel, Gurudev Dutt, Xiaoqin Li, Yanwen Wu, Jun Chen, D. Gammon, LJ Sham, "Optical control of spin in semiconductor dots for quantum operation," ITAMP, Harvard, 2004

CONTRIBUTED

(11) Yanwen Wu, Xiaoqin Li, D. G. Steel, D. Gammon, D. S. Katzer, D. Park, L. J. Sham , "Qubit Rotation with Multiple Phase-locked Pulses in Single Quantum Dots," QELS 2003.

(12) Xiaoqin Li, Yanwen Wu, D. G. Steel, D. Gammon, D. S. Katzer, D. Parker and L. J. Sham , "Raman Quantum Beats from the Entangled Exciton Zeeman Doublet in a Single Quantum Dot," QELS 2003

(13) Yanwen Wu, Xiaoqin Li, D.G. Steel, A.S. Bracker, D. Gammon, L.J. Sham "A complete mapping of the density matrix of a qubit in a single quantum dot," IQEC (2004).

(14) Xiaoqin Li, Yanwen Wu, D.G. Steel, D. Gammon, L.J. Sham "An optical Controlled-NOT gate in a single quantum dot," IQEC (2004).

(15) Xiaodong Xu, Jun Cheng, M. V. Gurudev Dutt, Yanwen Wu and D. G. Steel A. S. Bracker and D. Gammon, Renbao Liu, Sophia E. Economou and L. J. Sham, "Optically Stimulated and Spontaneously

Generated Electron Spin Coherence in Quantum Dots" QELS/CLEO 2005

Brief Outline of Research Findings:

Objective

This work focuses on the study and development of doped semiconductor quantum dots (QD) for application to the problem of optically driven quantum computing. In a doped quantum dot, the qubit is the spin.

The developments in this field are based on the recent advances in fabrication and nano-optical-probing and the new developments of our own group that have contributed with the first measurements and theory in coherent nonlinear optical manipulation of these systems.

Approach

Our approach to the study of these systems is based on the use of coherent nonlinear laser spectroscopy, coherent transient excitation and optical control, and the use of advanced materials. The qubit of interest is the electron spin confined to a semiconductor quantum dot. Coherent control of the system is achieved by coherent optical excitation using the trion state as the intermediate state, thus allowing optical frequencies (eV) to be used to manipulate the spin states, separate by 10's of μeV. Materials are grown by MBE and further processing by lithography techniques by Dan Gammon and his group at NRL. For experiments designed to test our optical measurement schemes, such as our work on density matrix tomography of quantum dots (discussed earlier and below), the system of interest is based on the neutral quantum dot. Work on neutral quantum dots was the focus on the earlier parent program that paralleled this QuaCGR grant.

A scalable architecture for electron spin based qubits in charged quantum dots has been published by us (with Lu J. Sham, UC-SD). The qubit can experience an arbitrary rotation by excitation through a virtually excited trion state using a coherent Raman type excitation. Entanglement between spin in adjacent dots is accomplished by a modified optical RKKY (ORKKY) interaction based on a Heisenberg Hamiltonian coupling between the two spins.

Figure 1 shows the basic idea of a quantum dot spin qubit shown in the single particle picture and shows the difference between the two degenerate ground states. By adding a single electron to the quantum dot, the ground state of this system becomes doubly degenerate and is known to exhibit long relaxation times, relative to the exciton relaxation time. The long relaxation time is expected to lead to long coherence times. A scalable system is achieved by creating an array of such dots within a few 10's of nanometers of each other. The usually forbidden optical transition between the trion state and the other spin state is allowed in the presence of a magnetic field in x-direction (Voight profile). Coherent optical control of the spin states is then enabled through a stimulated Raman two-photon (SR2P) pathway, shown by the red and green arrows.

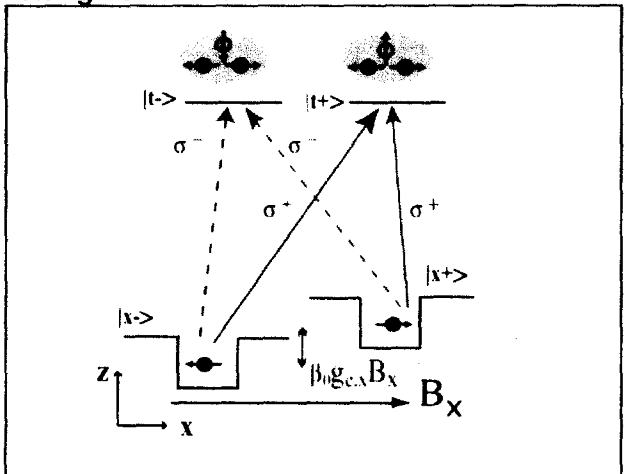

Figure 1 Excitation picture for the charged quantum dot, with ground states labeled by electron spin states

along the x-axis split by $\beta_0 g_{e_x} B_x$, and trion states labeled by the heavy-hole angular momentum projection along z-axis, as explained in the text. Solid (dashed) lines denote transitions excited by light. $\sigma^+(\sigma^-)$

Progress

Nearly all of the research findings discussed in the above publications have been presented in the earlier progress reports. However, we summarize below the major achievement during the last research period. The work in this program is done in collaboration with the fabrication group headed by Dan Gammon at NRL and the theory group headed by Lu Sham at UC-SD.

Density Matrix Tomography and Arbitrary Rotation of an Exciton Block Vector Qubit

While the new parent program is aimed exclusively at optically manipulating the electron spin in charged quantum dots, the previous parent program aimed at optically manipulating the exciton Bloch vector spin in neutral quantum dots that are better controlled and characterized in processing (because they are more established). This system provided us with the ideal ability to make the first demonstration of quantum state tomography of the density matrix and arbitrary qubit rotations in a solid state system.

Much of this has been detailed in previous reports. During this time, however, the work was completed and accepted for publication in Physical Review Letters. The results demonstrate single qubit density matrix tomography in a single semiconductor quantum dot system through consecutive phase sensitive rotations of the qubit via ultrafast coherent optical excitations. The result is important for quantifying gate operations in quantum information processing in the quantum dot systems as well as demonstrating consecutive arbitrary qubit rotations.

The primary new information that we developed during this period is that we completed the evaluation of the real and imaginary parts of the density matrix elements and also completed the error analysis of the data.

Figure 2 shows the results, where the color coding represents the real and imaginary parts of the density matrix for a single exciton Bloch vector qubit.

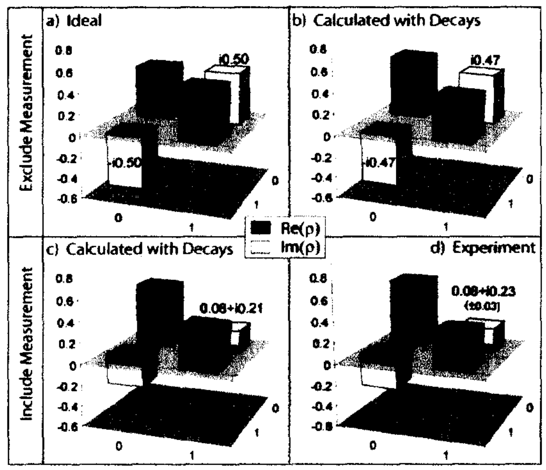

FIG. 2: Density matrices of a single qubit created by a $\pi/2$ pulse. (a) Ideal matrix. (b)((c)) Calculated density matrices with decays excluding (including) rotation and probe pulses. (d) Measured density matrix from experiment.

The discrepancies between the measured coherence (off-diagonal) terms in these density matrices and the theoretically expected values (see earlier reports) can be attributed to the measurement process represented by the rotation pulse. In numerical simulations including the measurement process (Fig. 2(c)), the density matrix elements are comparable to the measured values. The excellent agreement between Figs. 2(c) and 2(d) signifies that we have a complete knowledge of the quantum system used and that its behavior under excitation is completely theoretically predictable. We note that the population terms of all three density matrices are essentially the same. However, the coherence terms of the density matrices with the inclusion of the rotation pulses stray from their ideal values. Specifically, in the presence of the rotation pulse, the coherence terms have non-zero real components, while in the absence of a rotation pulse, they are purely imaginary regardless of the qubit lifetime. This apparent discrepancy arises from the short decoherence of the system and the temporal overlap of the first and the second pump pulses. Although the two 3 ps wide pump pulses are separated by 10 ps, the pulse tail of the first pulse and the pulse front of the second pulse overlap. The amount of overlap, though small, can still affect the accuracy of the measurement of the coherence terms. In the Bloch sphere representation, we can attribute the error to population decay and the simultaneous rotation of the Bloch vector by the creation and rotation pulses, both of which lead to a non-zero real component in the measured coherence terms. We can avoid simultaneous rotation of the Bloch vector by separating the two pulses further to eliminate overlaps, but the short decoherence between the qubit states $|0\rangle$ and $|1\rangle$ will begin to introduce greater error as the measurement is made at a larger delay. It may be that the discrepancies can be minimized by using a combination of pulse-shaping techniques on shorter pulses to avoid exciting nearby states. Quantum systems with longer decay times, such as the spin qubit system in charged QDs, would also minimize this error.

Spin Control in Single Charged Quantum Dots:

In the parent program, we discussed our use of two-photon Raman coherent transient excitation of the spin states to create and detect the spin coherence. In addition, we demonstrated that we can control the ensemble spin coherence. However, as a step towards demonstrating an arbitrary qubit rotation, we need to demonstrate that we can initialize the system, perform a rotation on the prepared state and then read it out. This amounts to a 3-pulse measurement, which we achieve using the setup shown in Figure 3.

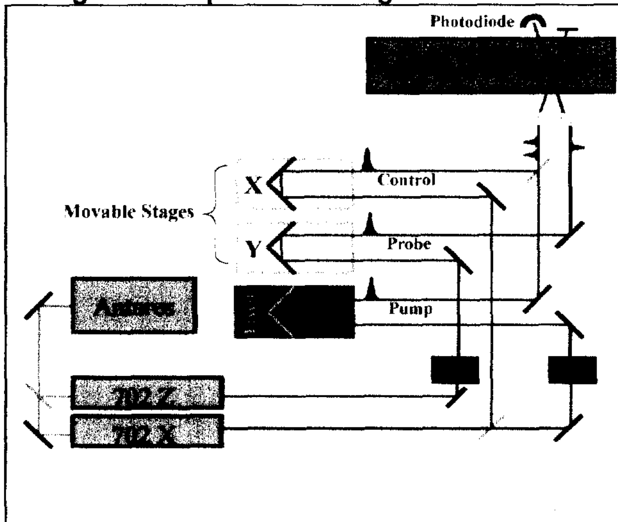

Figure 3. Experimental configuration for demonstrating initialization and control of the electron spin.

The corresponding double sided Feynman diagrams that describe the the initialization and the rotation are shown in Fig. 4 along with the corresponding effect on the Bloch sphere for the spin

Using the setup in Fig. 3 and the excitation scheme in Fig. 4, we were then able to demonstrate initialization and control using the polarization coupling shown in Fig. 5a. Figure 5b shows the coherence as a function of time following initialization of the state in the absence of a control pulse. Figures 5c and d demonstrate the control o f the initialized state, where depending on the arrival of the control pulse (noted along the right hand side of the curve, we see amplitude of spin coherence is either enhanced or suppressed. This behavior is similar to Rabi oscillations in a 2-level system.

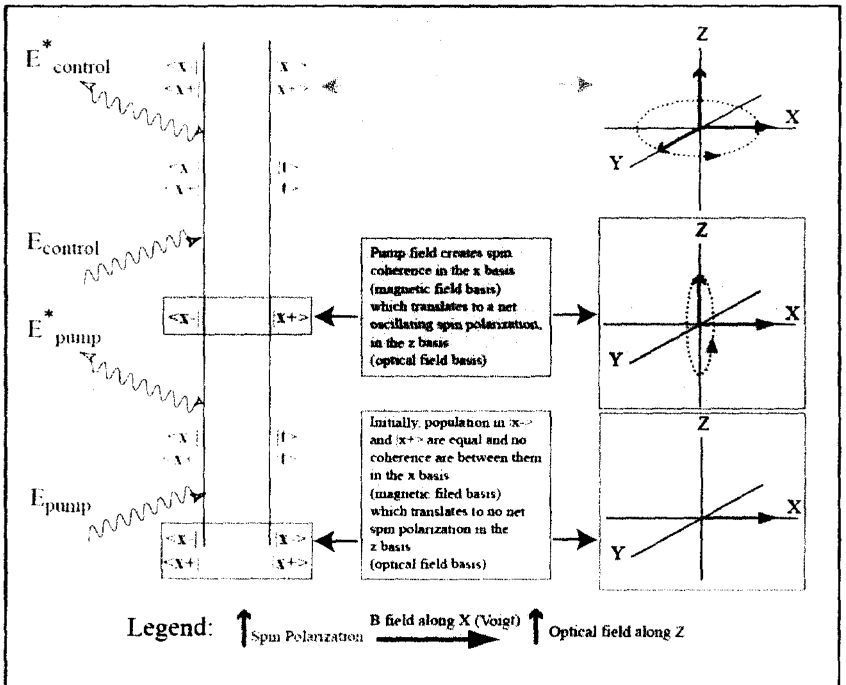

Figure 4. Double sided Feynman diagrams showing the optical interactions leading to initialization and control of the electron spin coherence using stimulated Raman excitation.

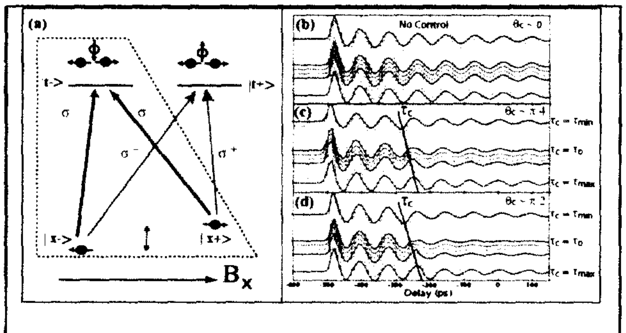

Figure 5. Experimental demonstration of initialization and control of spin polarization. Figure 5a: Energy level diagram in a single charged QD. |x±> are the spin ground states and |t±> are the trion states. The |x±> states are split by a magnetic field in the Voigt geometry which is perpendicular to the growth direction. A Λ system can be isolated by using σ_+ polarized light as seen in the dashed box. (b) to (d) Three-beam spin quantum beats with pump-probe pair and a control beam, where the control beam delay τ_c is varied from τ_{min} to τ_{max}. θ_c is the control pulse area, where $\theta_c = 0$ in (b), $\theta_c = \pi/4$ in (c), and $\theta_c = \pi/2$ in (d). By observing the spin amplitude change at $\tau_c = \tau_0$ for three different $\theta_c = 0, \pi/4, \pi/2$, we note that the extent of the spin rotation depends on the control pulse area. This behavior is analogous to the Rabi oscillations of a two-level system.